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CALCULATION OF THE RELATIONSHIP BETWEEN ATTENUATION AND INTENSITY OF PRECIPITATION FOR VARIOUS POLARIZATIONS

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CALCULATION OF THE RELATIONSHIP BETWEEN ATTENUATION AND INTENSITY OF PRECIPITATION FOR VARIOUS POLARIZATIONS

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Work carried out at the U. Bordoni Foundation with the current agreement between the P. T. Administration and the Ugo Bordoni Foundation

1. Introduction /1*

This evaluation is based on the following physical hypotheses:

i) distribution of average drop diameter according to Laws-Parson (B.1); distribution of deformations according to Magono (B.2);

ii) distribution of drop orientation so as to admit the existence of two principal propagation planes (B.3);

iii) uniform precipitation profile.

We do not assume, however, as in (B.2), that all drops have the same orientation nor that the axes are contained in the transverse plane. Adoption of these two hypotheses has always led to depolarization estimates higher than the ones measured (when the absence of ice was ascertained).

On the other hand, this would be expected because equal alighment corresponds to the worst conditions regarding depolarization.

It appears reasonable to adopt a parameter which permits a gradual "relaxing" of the severity of this assumption, starting from Oguchi's model and ending with a neutral model for polarization effects.

This can be done in various ways: In (B.4) Chi assumes a multiplier coefficient representing the ratio between the effective linear depolariza-

*Numbers in the margin indicate pagination of original foreign text.

tion and the depolarization obtained with Oguchi's model. In (B.6) a different parameter is proposed, representing the ratio between the effective differential propagation constant (concerning the principal planes) and the constant which is obtained with Oguchi's model. We prefer this approach to the problem, because it can be anchored to a concrete physical model of the orientation distribution. For this purpose, we assume to start with a situation corresponding to Oguchi's model. The common orientation of the drop axes, together with the propagation axes, define a plane designated here as principal plane I of the entire transmission medium (obviously, principal plane II is the one perpendicular to I).

We now assume a 90^{o} rotation of a fraction of the drops to change to II the symmetry axes of principal plane I of the medium. This operation is shown schematically in Fig. 1. /2

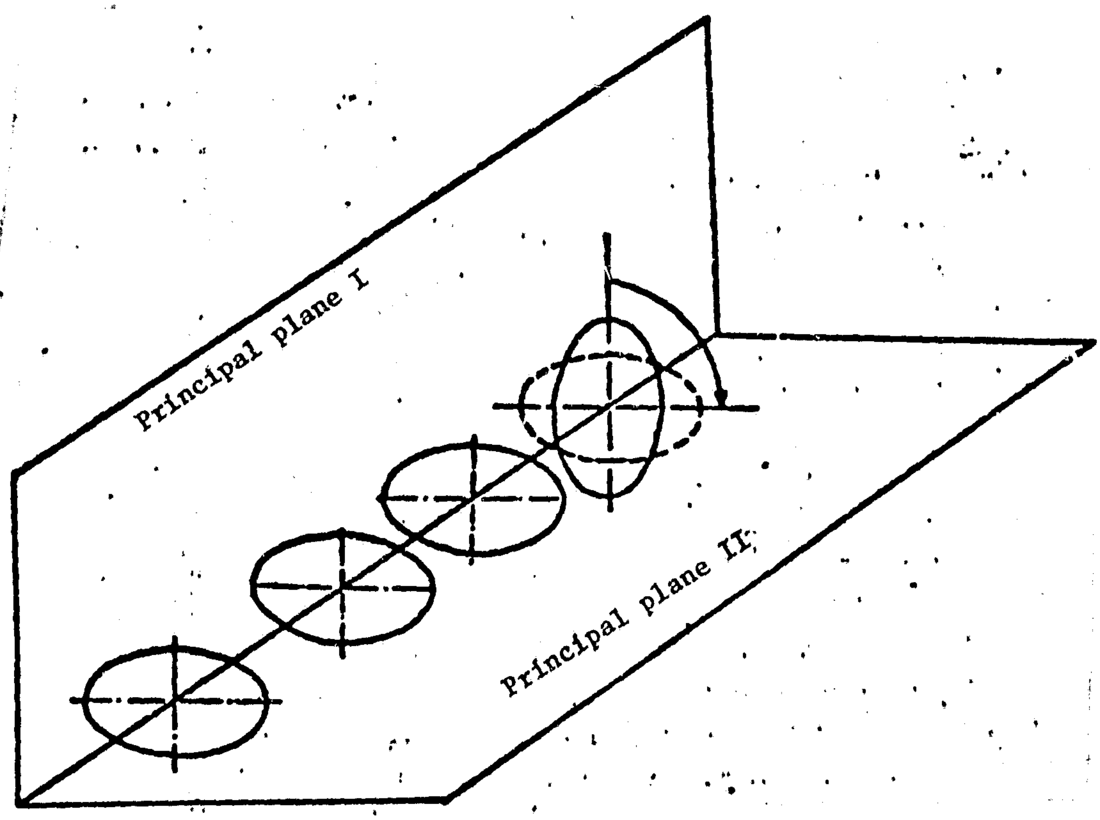

Fig. 1

Varying ε from 0 to 1/2, we change from a situation as in Oguchi's to a neutral situation concerning polarization effects.

The propagation constants along the two principal planes become:

$$\begin{aligned} \gamma_{I} &= (1-\varepsilon)\,\gamma_{I0} + \varepsilon\,\gamma_{II0} \\ \gamma_{II} &= \varepsilon\,\gamma_{I0} + (1-\varepsilon)\,\gamma_{II0} \end{aligned} \qquad (1)$$

where γ_{I0} and γ_{II0} are values according to Oguchi (available now at FUB*) they have been estimated using physical hypotheses (1)).

The physical meaning of parameter ε can be interpreted as a population 2ε neutralized with respect to polarization so that only the remaining fraction $p = 1-2\varepsilon$ remains active (p designates the "active fraction"). /3

System (1) can be described as a function of the active fraction as follows:

$$\begin{aligned} \gamma_{I} &= \left(\frac{1+p}{2}\right)\gamma_{I0} + \left(\frac{1-p}{2}\right)\gamma_{II0} \\ \gamma_{II} &= \left(\frac{1-p}{2}\right)\gamma_{I0} + \left(\frac{1+p}{2}\right)\gamma_{II0} \end{aligned} \qquad (2)$$

Of course, p varies between 0 and 1; for p = 0, the medium is neutral with respect to polarization effects, while for p = 1 the medium has the maximum depolarizing action.

One obtains from (2)

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*FUB = Ugo Bardoni Foundation

$$\frac{\gamma_{II} + \gamma_{I}}{2} = \frac{\gamma_{II0} + \gamma_{I0}}{2}$$

$$\frac{\gamma_{II} - \gamma_{I}}{2} = p\left(\frac{\gamma_{II0} - \gamma_{I0}}{2}\right) \qquad (3)$$

Parameter p is an equivalent parameter: for every case it is possible to determine it so as to adjust value $(\gamma_{II0}-\gamma_{I0})/2$ to the real value $(\gamma_{II}-\gamma_{I})/2$ (called "electric dissymmetry" of the medium) which can be obtained from measurements of circular depolarization.

A phenomenon which can be accounted for with a suitable value of p is a "spread" of the axes of the drops around an average direction (which determines the inclination of the principal planes); this spread can be described by an angular variation which can actually be related to p.

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2. The Algorithm

Similarly to what was described for the FUB relation (B.5), the state of polarization of the entering wave is described by the two parameters Ψ and α giving, respectively, the oscillation phase along the vertical axis y (with respect to the horizontal x) and a partition of the power between the two oscillations according to the $\cos^2\alpha$ and $\sin^2\alpha$ law.

In this way, we can express the wave entering the transmission channel as the product of a generic elliptic versor:

$$\vec{U}_{dir} = \begin{vmatrix} \cos\alpha \\ e^{j\Psi}\,\mathrm{Sen}\,\alpha \end{vmatrix} = (\cos\alpha)\,\vec{U}_x + \left(e^{j\Psi}\,\mathrm{Sen}\,\alpha\right)\vec{U}_y \qquad (4)$$

which transports specific unitary power for each α and Ψ, multiplied times the respective amplitude E_{dir} (generically complex).

The orthogonal elliptic versor $\vec{U}_{inc}$ is given by

$$\vec{U}_{inc} = \begin{vmatrix} \text{sen}\,\alpha \\ -e^{J\Psi}\cos\alpha \end{vmatrix} = (\text{sen}\,\alpha)\,\vec{U}_x + (-e^{J\Psi}\cos\alpha)\,\vec{U}_y \tag{5}$$

The transfer function of the channel is given by the matrix (B.3):

$$e^{-\left(\frac{\gamma_{II}+\gamma_{I}}{2}\right)\ell}\left\{ \text{ch}\left(\frac{\gamma_{II}-\gamma_{I}}{2}\right)\begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + \text{sh}\left(\frac{\gamma_{II}-\gamma_{I}}{2}\ell\right)\begin{vmatrix} -\text{Cos}\,2\varphi & -\text{Sen}\,2\varphi \\ -\text{Sen}\,2\varphi & \text{Cos}\,2\varphi \end{vmatrix} \right\} \tag{6}$$

connecting the two components E_x and E_y of the incoming wave with the analogous components of the outgoing wave.

Applying (4) and (5) to identity:

$$\vec{E} = E_x\vec{U}_x + E_y\vec{U}_y = E_{dir}\vec{U}_{dir} + E_{inc}\vec{U}_{inc} \tag{7}$$

one easily obtains the relationships between the components: /5

$$\begin{vmatrix} E_{dir} \\ E_{inc} \end{vmatrix} = \begin{Vmatrix} \cos\alpha & e^{-J\Psi}\text{sen}\,\alpha \\ \text{sen}\,\alpha & -e^{-J\Psi}\cos\alpha \end{Vmatrix} \cdot \begin{vmatrix} E_x \\ E_y \end{vmatrix} \tag{8}$$

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{Vmatrix} \cos\alpha & \text{sen}\,\alpha \\ e^{J\Psi}\text{sen}\,\alpha & -e^{J\Psi}\cos\alpha \end{Vmatrix} \cdot \begin{vmatrix} E_{dir} \\ E_{inc} \end{vmatrix} \tag{9}$$

The behavior of the channel in a generic polarization can be described, therefore, by first applying (9) which supplies the orthogonal components pertinent to the generic wave, as a function of the elliptic components E_{dir} and E_{inc}.

One subsequently applies (6) and then (8), which then provides the elliptic components.

The matrix product leads to an equation analogous to (6) where, in place of the last matrix, a generic characteristic matrix appears:

$$|a| \equiv \begin{Vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{Vmatrix} \qquad (10)$$

where

$$\begin{aligned} a_{11} &= -\mathrm{Cos}2\alpha\,\mathrm{Cos}2\varphi - \mathrm{Sen}2\alpha\,\mathrm{Sen}2\varphi\,\mathrm{Cos}\psi \\ a_{12} &= \mathrm{Cos}2\alpha\,\mathrm{Sen}2\varphi\,\mathrm{Cos}\psi - \mathrm{Cos}2\varphi\,\mathrm{Sen}2\alpha + J\,\mathrm{Sen}2\varphi\,\mathrm{Sen}\psi \\ a_{22} &= -a_{11} \\ a_{21} &= a_{12}^{*} \end{aligned} \qquad (11)$$

One has, therefore, the matrix description: /6

$$\begin{vmatrix} E_{dir,out} \\ E_{inc,out} \end{vmatrix} = e^{\frac{-(\gamma_{II}+\gamma_{I})}{2}\ell} \left\{ \mathrm{Ch}\,\frac{\gamma_{II}-\gamma_{I}}{2}\ell\,|U| + \mathrm{Sh}\,\frac{\gamma_{II}-\gamma_{I}}{2}\ell\,|a| \right\} \cdot \begin{vmatrix} E_{dir,in} \\ E_{inc,in} \end{vmatrix} \qquad (12)$$

where $|U|$ is the unit matrix and subscripts "out" and "in" indicate exit from and entrance to the channel.

For $\alpha = 0$, $\psi = \pi$, (12) corresponds with (6).

For a circular polarization (E_{dir} = left circular polarization, E_{inc} = right circular polarization), one has: $\alpha = \pi/4$, $\psi = \pi/2$, and $|a|$ becomes:

$$|a| = \begin{vmatrix} 0 & -e^{-j2\varphi} \\ -e^{j2\varphi} & 0 \end{vmatrix} \tag{13}$$

In conclusion, the attenuation, which here concerns a generically polarized wave, is given by the ratio between the two analogous entrance and exit terms:

$$\frac{E_{dir,out}}{E_{dir,in}} = e^{-\left(\frac{\gamma_{IIo}+\gamma_{Io}}{2}\right)\ell}\left\{Ch\left(p\,\frac{\gamma_{IIo}-\gamma_{Io}}{2}\,\ell\right) + Sh\left(p\,\frac{\gamma_{IIo}-\gamma_{Io}}{2}\,\ell\right)a_{11}\right\}$$

$$\frac{E_{inc,out}}{E_{inc,in}} = e^{-\left(\frac{\gamma_{IIo}+\gamma_{Io}}{2}\right)\ell}\left\{Ch\left(p\,\frac{\gamma_{IIo}-\gamma_{Io}}{2}\,\ell\right) - Sh\left(p\,\frac{\gamma_{IIo}-\gamma_{Io}}{2}\,\ell\right)a_{11}\right\} \tag{14}$$

where (3) was used. One has to remember that the γ_{Io} and γ_{IIo} propagation constants of Oguchi have to be expressed in natural units (neper and radiants). /7

In conclusion, one observes that the attenuation and the phase difference for a generic polarization can be conveniently expressed as the sum of an average contribution (equal to the arithmetic average of attenuations and phase differences according to the principal planes of Oguchi's model with drops having the same orientation), and of a variation given by the modules and the argument of:

$$Ch\left(p\,\frac{\gamma_{IIo}-\gamma_{Io}}{2}\,\ell\right) \pm Sh\left(p\,\frac{\gamma_{IIo}-\gamma_{Io}}{2}\,\ell\right)a_{11} \tag{15}$$

(eventually expressed in engineering units (dB and degrees)).

Relations (14) were calculated at the frequencies of 17.8 and 30 GHz based on the specific attenuation and phase difference values determined at FUB (B.7 and 8). These are based on the electromagnetic theory of the equivalent layer for various polarization types, relative to various α and Ψ values reported in Table A (B.5).

The results obtained are reported in Tables 1 to 6 for the frequency of 17.8 GHz and 6 to 12 for the frequency of 30 GHz. The polarizations considered are, besides polarization H and polarization B, the left and right circular polarizations, the linear bisecting polarization of the first and third quadrant, and the one of the second and fourth quadrant.

The most significant channel parameters are:

A_m (dB/Km) : average attenuation $= \frac{A_{II} + A_I}{2}$

(where (II and I indicate the directions shown in Figure 1)

ΔA (dB/Km) : variation of attenuation of average value (equation 15)

A_a (dB/Km) : absolute attenuation equal to the sum of the average value of the attenuation and to the corresponding variation

$A_{II}-A_I$ (dB/Km) : differential attenuation along the two principal planes of the precipitation.

The same meaning can be attributed to the values reported for the phases, based on the following physical hypotheses: /8

-- Drop diameter distribution: Laws and Parsons
-- Drop ellipticity: Magono
-- Active drop population P: 100%
-- Principal planes inclination: 15°
-- Tract length: 1 km

The most significant values calculated with variation of ϕ were listed in the tables mentioned above and plotted in Figs. 2, 3, 4 and 5, to observe the influence of the inclination parameter on the principal planes ϕ.

The behavior of the six polarizations of interest, of the absolute attenuations, and of the absolute phase difference for angles included between 0° and 45° were reported in Figs. 2 and 3. The 45° limit was selected because this is the value of ϕ where polarizations M and V undergo attenuations and phase changes equal for both and identical to the ones undergone by the circular left or right polarizations (the behavior of the two polarizations is identical); all of this can easily be deduced analytically from the previous expressions (14). The two figures can be extended immediately to ϕ ranging from 45° to 90° because this range is symmetrical to the one from 0 to 45° once the corresponding polarizations are interchanged (for example, H with V).

The behavior of discriminations of the polarization into modulus and argument (B.5), still calculated as a function of ϕ, was reported in Figs. 4 and 5.

All values are pertinent to a precipitation intensity of 100 mm/h and a frequency of 30 GHz.

3. Conclusions

It can be observed in Figs. 2 and 3 that the attenuations and phase differences in right and left circular polarizations are equal and intermediate between the values of the M and V polarizations (equivalent to the linear bisecting polarizations of the first and second quadrant and of the second and fourth quadrant).

The behavior of the attenuation and of the phase difference for the bisecting linear polarizations is opposite to the one of the linear polarizations H and V for obvious symmetry reasons of the transmitting medium.

The circular polarizations are attenuated and changed in phase quantitatively in an amount which is different from the average of the attenuations of the linear polarizations H and V; the values of attenuation and phase difference are closer to the ones of the polarization B than to the ones of the polarization H. /9

The absolute attenuation and phase difference in circular polarization are also independent of the inclination of the principal planes of the precipitation.

We can conclude, therefore, that an absolute attenuation measure of the circular polarization cannot be used in any way to obtain information on the average attitude of the drops; however, there is the advantage of eliminating an unknown parameter in the comparison between theoretical and experimental values of attenuation for the evaluation of the average intensity of precipitation.

The discrimination of the polarization into a modulus (Fig. 4) for circular polarizations does not depend on the average attitude of the drops, which, on the other hand, has a determining influence on the modulus of linear discriminations.

The argument of discrimination has instead an opposite behavior (Fig. 5).

Therefore, the experimental verification of the performance of a possible relationship using linear polarization H and V for discrimination of the signals is difficult to carry out because, if the average attitude is close to zero (it now seems ascertained and acknowledged that $0 < \varphi < 10$), the level of the cross-polar signals is extremely small and, therefore, extremely strong dynamics would be required for their evaluation.

For this purpose, it is best to use the linear bisecting polarizations of the first and third quadrant or the one of the second and fourth, or the circular polarizations. These offer the advantage of a good cross-polar signal insensitive to variations of drop attitude.

If one is not concerned with the verification of the performance of possible operational systems, but rather with the study of the physical aspects of the propagation phenomenon, the physical parameters of higher interest are the anisotropy of the transmitting medium (difference between the propagation constants along the principal planes) and the average angle of the raindrops.

The results of the theoretical investigation are presented in the curves shown in Figs. 2, 3, 4 and 5. The following conclusions can be drawn: /10

a) It is possible and advisable to measure angle ϕ using left and right circular polarizations with coherent detection of the argument of the polarization discrimination. It can be observed in Fig. 5 that the algebraic difference between the arguments of the right and left circular polarization is equal (except for differences of 360°) to the value of the average angle ϕ multiplied by four.

We could not carry out this evaluation using linear polarizations H and V or first and second quadrant, because the argument of the discrimina-

tion of linear polarization is practically insensitive to the value of the average angle.

b) Anisotropy can be evaluated using the modulus of the circular polarization discrimination because, as already seen for absolute attenuation and phase difference, it is independent from the attitude of the drops.

References /11

1. Laws and Parsons. The relation of raindrop size to intensity, Trans.Am. Geoph. Union., Vol. 24, 1943.

2. T. Oguchi. Differential attenuation and differential phase shift of radio waves due to rain. IUCRM Colloquium Nice, France 1973.

3. C. Capsoni, A. Paraboni. Depolarization of an electromagnetic wave traveling through a stratified aerosol of non-spherical scatters. 18 AGARD meeting, Sept. 1972.

4. T. S. CHU. Rain-induced cross-polarization at centimeter and millimeter wavelengths. B.S.T.J., Vol. 53, N.B. October 1974.

5. D. Maggiori and A. Paraboni. "Calculation of cross-polarization as a function of the intensity of precipitation and/or of the attenuation," Ugo Bordoni Foundation (F.U.B.) report 1A2877, July 1977.

6. A. Attisani, C. Capsoni, A. Paraboni. IUCRM, colloguium Nice, France, 1973.

7. H. C. Van de Hulst. Light scattering by small particles, New York: John Wiley, 1957.

8. D. Maggiori. "Attenuation and depolarization of tropospheric propagation at frequencies higher than 10 GHz", F.U.B. Report 2yl, Rome, February 14, 1976.

α \ ψ	0	90	$\pm$ 180	-90
0	linear horizontal	linear horizontal	linear horizontal	linear horizontal
45	linear bisecting 1st and 3rd quadrant	circular left	linear bisecting 1st and 3rd quadrant	circular right
90	linear vertical	linear vertical	linear vertical	linear vertical

Table A

/13

TAB. 1

$F(CH_z) = 17.8$

Linear vertical polarization

$L = 1$ Km

$P = 100\%$

$\phi = 15°$

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{as} dB/Km	ϕm (gr./Km)	Δϕm (gr./Km)	ϕ_{as} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	9.820E-3	-2.487E-4	9.474E-3	6.738E-1	-9.891E-3	6.639E-1	7.991E-4	3.172E-2	-77.06	-99.45
1.25	6.568E-2	-2.984E-3	6.269E-2	2.661	-7.402E-2	2.587	6.897E-3	1.715E-1	-62.23	-104.93
2.5	1.492E-1	-7.525E-3	1.417E-1	4.807	-1.532E-1	4.654	1.740E-2	3.542E-1	-55.79	-108.31
5.0	3.327E-1	-1.993E-2	3.138E-1	8.663	-3.17E-1	8.346	4.381E-2	7.315E-1	-49.31	-111.87
12.5	9.42E-1	-6.22E-2	8.798E-1	18.692	-7.843E-1	17.91	1.441E-1	1.807	-4[illegible]06	-118.53
25.0	1.984	-1.507E-1	1.833	32.963	-1.642	31.323	3.496E-1	3.771	-34.45	-122.07
50.0	4.192	-3.742E-1	3.818	58.941	-3.298	55.643	8.688E-1	7.311	-28.07	-130.55
100.0	8.597	-9.138E-1	7.683	105.41	-6.532	98.878	2.109	14.607	-22.02	-139.83
150.0	12.991	-1.531	11.46	149.01	-9.566	139.44	3.504	21.02	-18.83	-146.57

TAB. 2

F (GHz) = 17.8

Linear horizontal polarization

L = 1 Km

P = 100%

ϕ = 15°

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{as} dB/Km	φm (gr./Km)	Δφm (gr./Km)	ϕ_{as} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	9.620E-3	3.462 E-4	1.017 E-2	6.738E-1	1.399 E-2	6.878	7.991E-4	3.472E-2	-75.25	-99.42
1.25	6.568E-2	2.989 E-3	6.867 E-2	2.661	7.435 E-2	2.735	6.597E-3	1.715E-1	-62.14	-104.78
2.5	1.492E-1	7.544 E-3	1.567 E-1	4.807	1.532 E-1	4.96	1.740E-2	3.342E-1	-55.74	-107.8
5.0	3.327E-1	1.801 E-2	3.517 E-1	8.663	3.165 E-1	8.98	6.381E-2	7.315E-1	-49.27	-111.24
12.5	9.42E-1	6.250 E-2	1.005	18.692	7.806 E-1	19.473	1.441E-1	1.807	-40.94	-116.06
25.0	1.984	1.521 E-1	2.136	32.965	1.623	34.588	3.[illegible]96E-1	3.771	-34.14	-119.81
50.0	4.192	3.781 E-1	4.57	58.941	3.205	62.146	8.63E-1	7.511	-27.32	-124.05
100.0	8.597	9.175 E-1	9.515	105.41	6.089	111.499	2.109	14.607	-20.19	-127.21
150.0	12.991	1.818	14.509	149.01	8.503	157.513	3.504	21.02	-15.78	-128.51

TAB. 3

$F\ (GHz) = 17.8$

Left circular polarization

$L = 1$ Km

$P = 100\%$

$\phi = 15°$

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{oe} dB/Km	φm (gr./Km)	Δφm (gr./Km)	$φ_{oe}$ (gr./Km)	$A_{II}-A_I$ (dB/Km)	$φ_{II}-φ_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	9.820E-3	3.093 E-7	9.82 E-3	6.738E-1	0	6.738 E-1	7.991E-4	3.472E-2	-71.04	-69.43
1.25	6.5[illegible]E-2	9.06 E-6	6.569 E-2	2.661	0	2.661	6.897E-3	1.715E-1	-56.2	-74.36
2.5	1.492E-1	3.715 E-5	1.492 E-1	4.807	0	4.807	1.740E-2	3.542E-1	-49.76	-77.96
5.0	3.327E-1	1.494 E-4	3.328 E-1	8.663	0	8.663	4.381E-2	7.315E-1	-43.27	-81.56
12.5	9.42E-1	7.811 E-4	9.428 E-1	18.692	-9.891 E-3	18.692	1.441E-1	1.8[illegible]7	-34.98	-87.75
25.0	1.984	2.943 E-3	1.987	32.965	-3.831 E-2	32.927	3.496E-1	3.771	-28.27	-91.47
50.0	4.192	7.787 E-3	4.20	58.941	-1.878 E-1	58.753	8.68E-1	7.511	-21.67	-97.[illegible]4
100.0	8.597	5.883 E-3	8.603	105.41	-8.869 E-1	104.523	2.109	14.607	-15.08	-104.19
150.0	12.991	-3.447 E-2	12.957	149.01	-2.114	146.896	3.504	21.02	-11.31	-109.12

TAB. 4

F (GH_z) = 17.8

Right circular polarization

L = 1 Km

P = 100%

ϕ = 15°

R (mm/h)	$\bar{A}m$ (dB/Km)	ΔAm (dB/Km)	A_{as} dB/Km	ϕm (gr./Km)	$\Delta\phi m$ (gr./Km)	ϕ_{as} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	$\angle$XPD (gr.)
0.25	9.820E-3	3.883 E-7	9.82 E-3	6.738E-1	0	6.738 E-1	7.991E-4	3.472E-2	-71.04	-129.43
1.25	6.568E-2	9.06 E-6	6.569 E-2	2.661	0	2.661	6.897E-3	1.715E-1	-56.2	-134.86
2.5	1.492E-1	3.715 E-5	1.492 E-1	4.807	0	4.807	1.740E-2	3.542E-1	-49.76	-137.95
5.0	3.327E-1	1.494 E-4	3.328 E-1	8.663	0	8.663	4.381E-2	7.315E-1	-43.27	-141.57
12.5	9.42E-1	7.811 E-4	9.428 E-1	18.692	-6.891 E-3	18.682	1.441E-1	1.807	-34.98	-147.75
25.0	1.984	2.943 E-3	1.987	32.965	-3.831 E-2	32.927	3.496E-1	3.771	-28.27	-151.47
50.0	4.192	7.787 E-3	4.20	58.941	-1.870 E-1	58.753	8.68E-1	7.311	-21.67	-157.44
100.0	8.597	5.883 E-3	8.603	105.41	-8.869 E-1	104.523	2.109	14.807	-15.08	-164.19
150.0	12.991	-3.447E-2	12.957	149.01	-2.114	146.896	3.504	21.02	-11.31	-169.12

TAB. 5

$F(\mathrm{GH_z}) = 17.8$

Linear bisecting polarization, I and II quadrant

$L = 1$ Km

$P = 100\%$

$\phi = 15°$

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	Aaa dB/Km	φm (gr./Km)	Δφm (gr./Km)	φaa (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	9.820E-3	2.001 E-4	1.002 E-3	6.738E-1	9.891 E-3	6.837 E-1	7.991E-6	3.472E-2	-88	180
1.25	6.568E-2	1.731 E-3	6.742 E-2	2.661	1.311 E-2	2.701	6.897E-3	1.715E-1	-57.45	-104.82
2.5	1.492E-1	4.378 E-3	1.536 E-1	4.807	8.847 E-2	5.692	1.740E-2	3.542E-1	-51.01	-107.86
5.0	3.327E-1	1.106 E-2	3.436 E-1	8.663	1.821 E-1	8.845	4.381E-2	7.315E-1	-44.51	-111.37
12.5	9.42E-1	3.441 E-2	9.786 E-1	18.692	4.462 E-1	19.136	1.441E-1	1.807	-36.2	-117.3
25.0	1.984	8.967 E-2	2.074	32.965	9.143 E-1	33.879	3.496E-1	3.772	-29.43	-120.52
50.0	4.192	2.234 E-1	4.415	58.941	1.735	60.676	8.68E-1	7.311	-22.71	-125.52
100.0	8.397	5.364 E-1	9.133	105.41	2.961	106.371	2.109	14.607	-15.8	-130.34
150.0	12.991	8.652 E-1	13.856	149.01	3.548	152.558	3.504	21.02	-11.66	-133.46

TAB. 6

F (GHz) = 17.8

Linear bisecting polarization, II and IV quadrant

L = 1 Km

P = 100%

ϕ = 15°

R (mm/h)	A_m (dB/Km)	ΔA_m (dB/Km)	A_{as} dB/Km	Φ_m (gr./Km)	$\Delta\Phi_m$ (gr./Km)	Φ_{as} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\Phi_{II}-\Phi_I$ (gr./Km)	|XPD| (dB)	$\angle$XPD (gr.)
0.25	9.820E-3	-1.993 E-4	9.621 E-3	6.738E-1	0	6.738 E-1	7.991E-4	3.472E-2	-87.99	-179.98
1.25	6.368E-2	-1.717 E-3	6.396 E-2	2.661	-4.196 E-2	2.619	6.897E-3	1.715E-1	-57.46	-104.91
2.5	1.492E-1	-4.322 E-3	1.449 E-1	4.807	-8.847 E-2	4.719	1.740E-2	3.542E-1	-51.02	-108.08
5,0	3.327E-1	-1.084 E-2	3.219 E-1	8.663	-1.835 E-1	8.48	4.381E-2	7.315E-1	-44.53	-111.74
12.5	9.42E-1	-3.544 E-2	9.066 E-1	18.692	-4.574 E-1	18.235	1.441E-1	1.807	-36.27	-118.2
25.0	1.984	-8.525 E-2	1.899	32.965	-9.712 E-1	31.994	3.496E-1	3.778	-29.64	-122.41
50.0	4.192	-2.117 E-1	3.98	58.941	-2.017	56.924	8.68E-1	7.512	-23.14	-129.27
100.0	8.597	-5.268 E-1	8.07	105.41	-4.291	101.119	2.109	14.607	-15.87	-137.6
150.0	12.991	-9.125 E-1	12.079	149.01	-6.727	142.283	3.504	21.02	-13.44	-143.74

TAB. 7

F (GHz) = 30.0

Linear vertical polarization

L = 1 Km

P = 100%

θ = 15°

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{ns} dB/Km	φm (gr./Km)	Δφm (gr./Km)	ϕ_{ns} (gr./Km)	$A_{II}-A_{I}$ (dB/Km)	$\phi_{II}-\phi_{I}$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	3.507E-2	-1.231 E-3	3.384 E-2	1.131	-2.212 E-2	1.109	2.845E-3	5.37E-2	-72.1	-109.28
1.25	2.084E-1	-1.022 E-2	1.982 E-1	4.28	-1.17 E-1	4.163	2.361E-2	2.705E-1	-57.33	-120.05
2.5	4.428E-1	-2.488 E-2	4.179 E-1	7.511	-2.28 E-1	7.283	5.749E-2	5.265E-1	-50.98	-125.99
5.0	9.264E-1	-5.916 E-2	8.672 E-1	13.07	-4.262 E-1	12.644	1.366E-1	9.82E-1	-44.77	-132.98
12.5	2.411	-1.797 E-1	2.231	26.49	-9.268 E-1	25.563	4.144E-1	2.126	-36.59	-143.04
25.0	4.778	-3.904 E-1	4.388	44.324	-1.52	42.804	8.973E-1	3.461	-30.67	-151.17
50.0	9.465	-8.437 E-1	8.621	73.99	-2.285	71.705	1.924	5.127	-25.31	-160.19
100.0	18.136	-1.714	16.422	122.36	-2.756	119.604	3.898	6.04	-20.49	-169.31
150.0	26.262	-2.577	23.685	165.18	-2.776	162.404	5.73	5.98	-17.97	-172.46

TAB. 8

$T\ (^{\circ}K_s) = 30.0$

Linear horizontal polarization

L = 1 Km

P = 100%

ϕ = 15°

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{ss} dB/Km	ϕm (gr./Km)	Δϕm (gr./Km)	ϕ_{ss} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	3.567E-2	4.232 E-3	3.63 E-2	1.131	2.423 E-2	1.155	2.845E-3	5.37E-2	-71.28	-109.24
1.25	2.084E-1	1.023 E-2	2.186 E-1	4.28	1.172 E-1	4.397	2.361E-2	2.705E-1	-57.3	-118.81
2.5	4.428E-1	2.49 E-2	4.677 E-1	7.511	2.278 E-1	7.739	5.749E-2	5.265E-1	-50.94	-125.53
5.0	9.264E-1	5.919 E-2	9.856 E-1	13.07	4.242 E-1	13.494	1.366E-1	9.82E-1	-44.65	-132.13
12.5	2.411	1.732 E-1	2.59	26.49	9.141 E-1	27.404	4.144E-1	2.126	-36.23	-141.2
25.0	4.739	8.966 E-1	5.655	44.324	1.475	45.799	8.973E-1	3.461	-30.09	-148.18
50.0	9.465	8.214 E-1	10.236	73.99	2.142	76.132	1.924	5.127	-23.64	-155.76
100.0	13.35[illegible]	1.63	19.786	122.36	2.41	124.77	3.898	6.04	-17.07	-164.14
150.0	26.262	2.343	28.605	165.18	2.262	167.442	5.73	5.98	-13.05	-168.42

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TAB. 9

F (GHz) = 30.0

Left circular polarization

L = 1 Km

P = 100%

ϕ = 45°

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{eq} dB/Km	ϕE (gr./Km)	$\Delta\phi m$ (gr./Km)	ϕ_{eq} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	3.507E-2	6.412 E-7	3.507 E-2	1.131	0	1.131	2.845E-3	5.37E-2	-66.08	-78.26
1.25	[illegible]4E-1	1.624 E-5	2.0[illegible] E-1	4.28	0	4.28	2.361E-2	2.705E-1	-51.3	-89.95
2.5	4.425E-1	4.414 E-5	4.428 E-1	7.511	0	7.511	5.749E-2	5.265E-1	-44.94	-95.77
5.0	9.264E-1	5.022 E-5	9.265 E-1	13.07	0	13.07	1.366E-1	9.82E-1	-38.69	-102.55
12.5	2.411	-9.769 E-4	2.41	26.49	-2.423 E-2	26.466	4.144E-1	2.126	-33.39	-112.14
25.0	4.778	-7.63 E-3	4.77	44.324	-8.902 E-2	44.235	8.973E-1	3.461	-24.47	-118.74
50.0	9.465	-4.456 E-2	9.42	73.99	-2.827 E-1	73.707	1.924	5.127	-18.49	-128.19
100.0	18.156	-2.054 E-1	17.951	122.36	-6.671 E-1	121.693	3.898	6.04	-12.88	-137.22
150.0	26.262	-4.535 E-1	25.809	165.18	-9.527 E-1	164.227	5.73	5.98	- 9.85	-141.64

TAB. 10

$F\ (GHz) = 30.0$

Right circular polarization

$L = 1\ Km$

$P = 100\%$

$\phi = 15°$

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{ag} dB/Km	ϕm (gr./Km)	Δϕm (gr./Km)	ϕ_{ag} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	3.507E-2	8.413 E-7	3.507 E-2	1.131	0	1.131	2.845E-3	5.37E-2	-66.08	-139.26
1.25	2.084E-1	1.624 E-5	2.084 E-1	4.28	0	4.28	2.361E-2	2.705E-1	-51.3	-149.93
2.5	4.428E-1	1.414 E-5	4.428 E-1	7.511	0	7.511	5.749E-2	5.265E-1	-44.94	-155.77
5.0	9.264E-1	5.022 E-5	9.265 E-1	13.07	0	13.07	1.366E-1	9.82E-1	-38.69	-162.55
12.5	2.411	-9.769 E-4	2.41	26.49	-2.423 E-2	26.466	4.144E-1	2.126	-30.39	-172.14
25.0	4.778	-7.63 E-3	4.77	44.324	-8.9c2 E-2	44.235	8.973E-1	3.461	-24.47	-178.74
50.0	9.465	-4.456 E-2	9.42	73.99	-2.827 E-1	73.707	1.924	5.127	-18.49	171.81
100.0	18.136	-2.054 E-1	17.951	122.36	-6.671 E-1	121.693	3.898	8.04	-12.88	162.78
150.0	26.262	-4.535 E-1	25.809	165.18	-9.527 E-1	164.227	5.73	5.98	-8.83	158.36

TAB. 11

F (GHz) = 30.0

Linear bisecting polarization, I and III quadrant

L = 1 Km

P = 100%

$\phi = 45°$

R (mm/h)	A_m (dB/Km)	ΔA_m (dB/Km)	A_{me} dB/Km	ϕ_m (gr./Km)	$\Delta\phi_m$ (gr./Km)	ϕ_{me} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	$\angle$XPD (gr.)
0.25	3.507E-2	7.119 E-4	3.578 E-2	1.131	1.399 E-2	1.145	2.843E-3	5.37E-[illegible]	-76.97	180
1.25	2.084E-1	5.815 E-3	2.143 E-1	4.28	6.745 E-2	4.347	2.361E-2	2.705E-1	-52.54	-119.87
2.5	4.428E-1	1.441 E-2	4.572 E-1	7.511	1.308 E-1	7.642	5.749E-2	3.265E-1	-46.18	-125.64
5.0	9.264E-1	3.42 E-2	9.606 E-1	13.07	2.426 E-1	13.313	1.366E-1	9.82E-1	-39.9	-132.31
12.5	2.411	1.029 E-1	2.514	26.49	5.123 E-1	27.002	4.144E-1	2.126	-31.54	-141.61
25.0	4.778	2.186 E-1	4.997	44.324	7.967 E-1	45.121	8.973E-1	3.461	-25.49	-149.86
50.0	9.465	4.467 E-1	9.912	73.99	1.058	75.048	1.924	5.127	-19.25	-156.85
100.0	18.156	8.096 E-1	18.966	122.36	9.489 E-1	123.309	3.898	6.04	-13.12	-165.61
150.0	26.262	1.053	27.315	165.18	6.464 E-1	165.826	5.73	5.98	-6.57	-170.04

TAB. 12

$F\ (GH_z) = 30.0$

Linear bisecting polarization, II and IV quadrant

$L = 1$ Km

$P = 100\%$

$\phi = 45°$

R (mm/h)	Am (dB/Km)	ΔAm (dB/Km)	A_{as} dB/Km	ϕm (gr./Km)	$\Delta\phi m$ (gr./Km)	ϕ_{as} (gr./Km)	$A_{II}-A_I$ (dB/Km)	$\phi_{II}-\phi_I$ (gr./Km)	|XPD| (dB)	∠XPD (gr.)
0.25	3.507E-2	-7.404 E-4	3.436 E-2	1.131	-9.891 E-3	1.121	2.845E-3	5.37E-2	-76.96	-190.00
1.25	2.084E-1	-5.69 E-3	2.025 E-1	4.28	-6.709 E-2	4.213	2.361E-2	2.705E-1	-52.55	-120.00
2.5	4.428E-1	-1.434 E-2	4.285 E-1	7.511	-1.32 E-1	7.379	5.749E-2	5.265E-1	-46.2	-125.9
5.0	9.264E-1	-3.413 E-2	8.923 E-1	13.07	-2.485 E-1	12.822	1.366E-1	9.82E-1	-35.97	-132.6
12.5	2.411	-1.043 E-1	2.307	26.49	-5.504 E-1	25.94	4.144E-1	2.126	-31.75	-142.67
25.0	4.778	-2 3 E-1	4.548	44.324	-9.307 E-1	43.393	8.973E-1	3.461	-25.94	-150.58
50.0	9.465	-5.136 E-1	8.951	73.99	-1.483	72.507	1.924	5.127	-20.206	-159.39
100.0	18.156	-1.119	17.037	122.36	-1.964	120.399	3.898	6.04	-15.05	-168.52
150.0	26.262	-1.741	24.521	165.18	-2.[illegible]32	163.068	5.73	5.98	-12.36	-172.8

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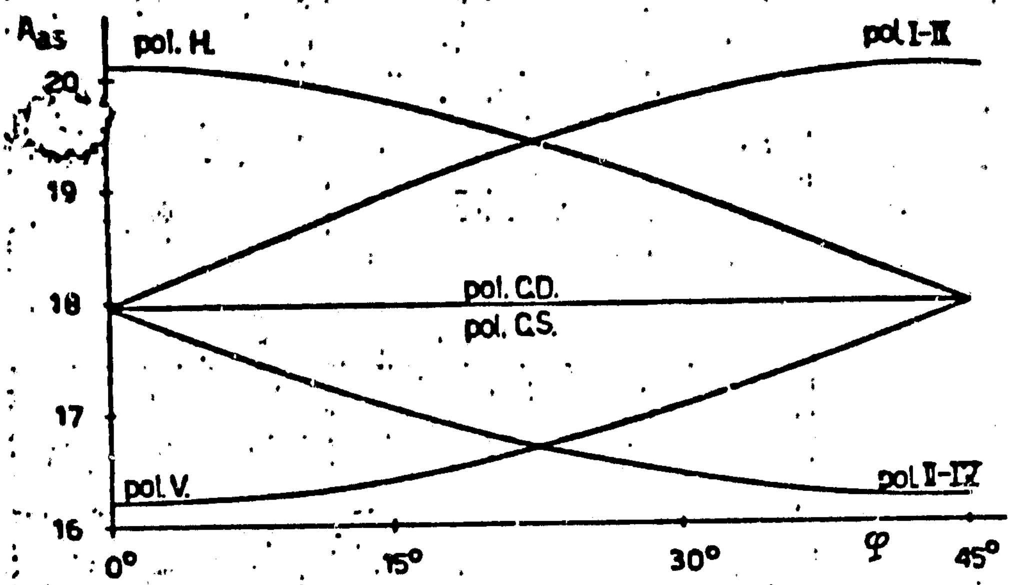
Aas
pol. H.
pol I-III
20
19
18
17
16
pol. C.D.
pol. C.S.
pol. V.
pol II-IV
0°
15°
30°
φ
45°

FIG. 2

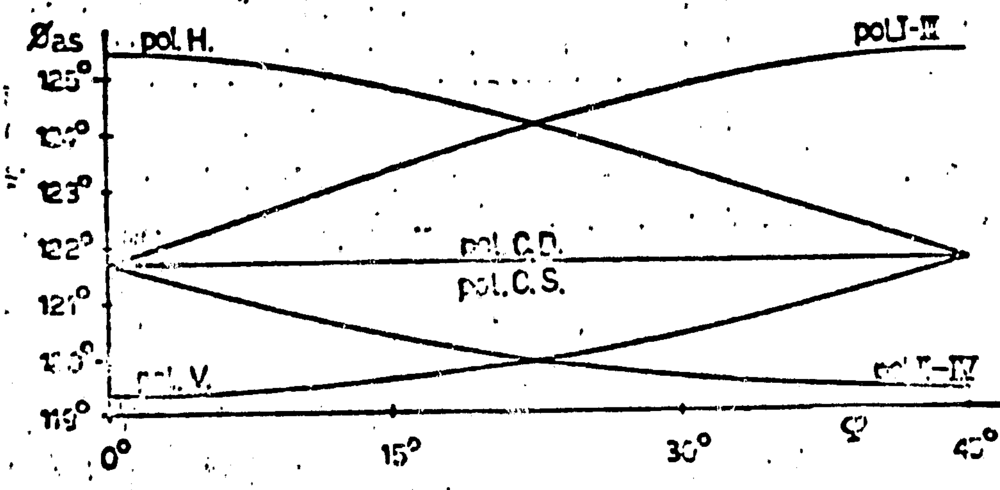
Øas
pol. H.
pol I-III
125°
123°
122°
121°
pol. C.D.
pol. C.S.
pol. V.
119°
0°
15°
30°

FIG. 3

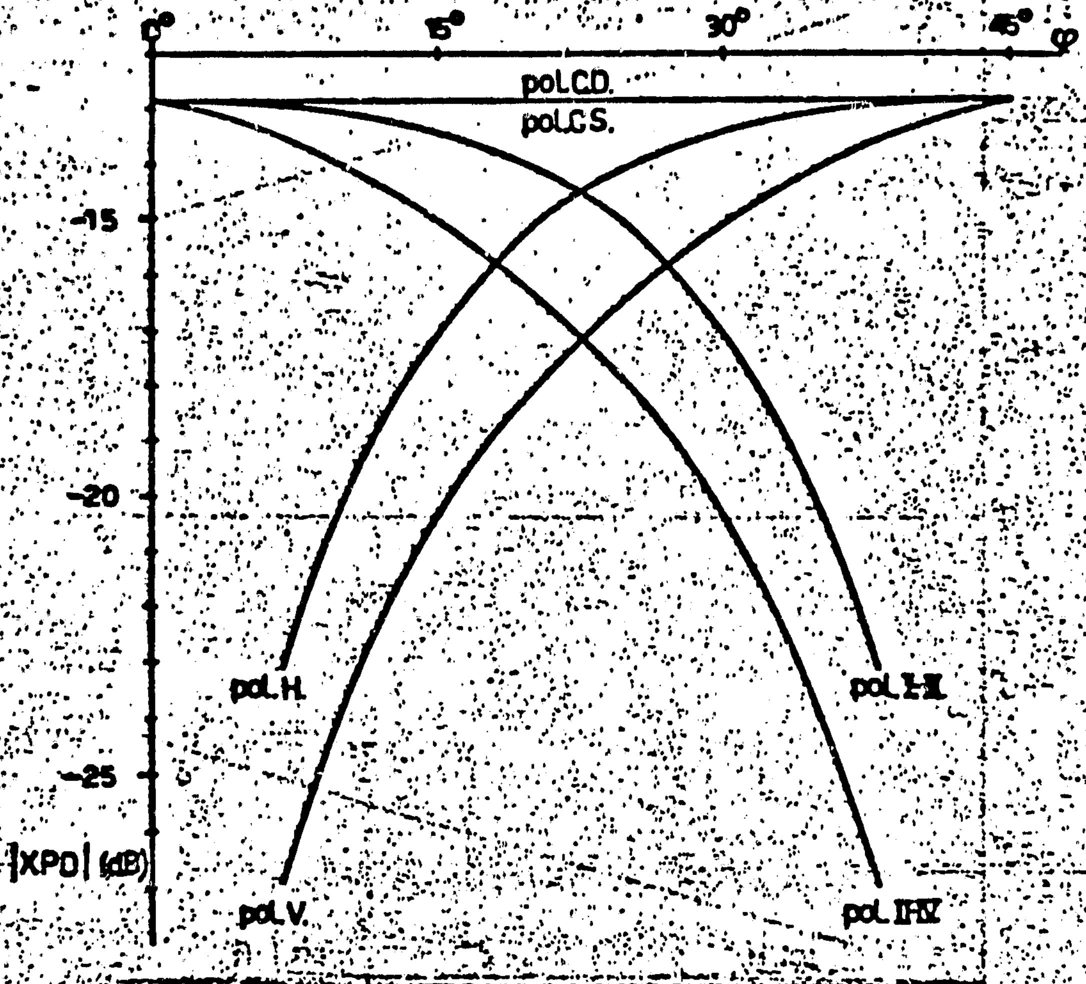

FIG. 4

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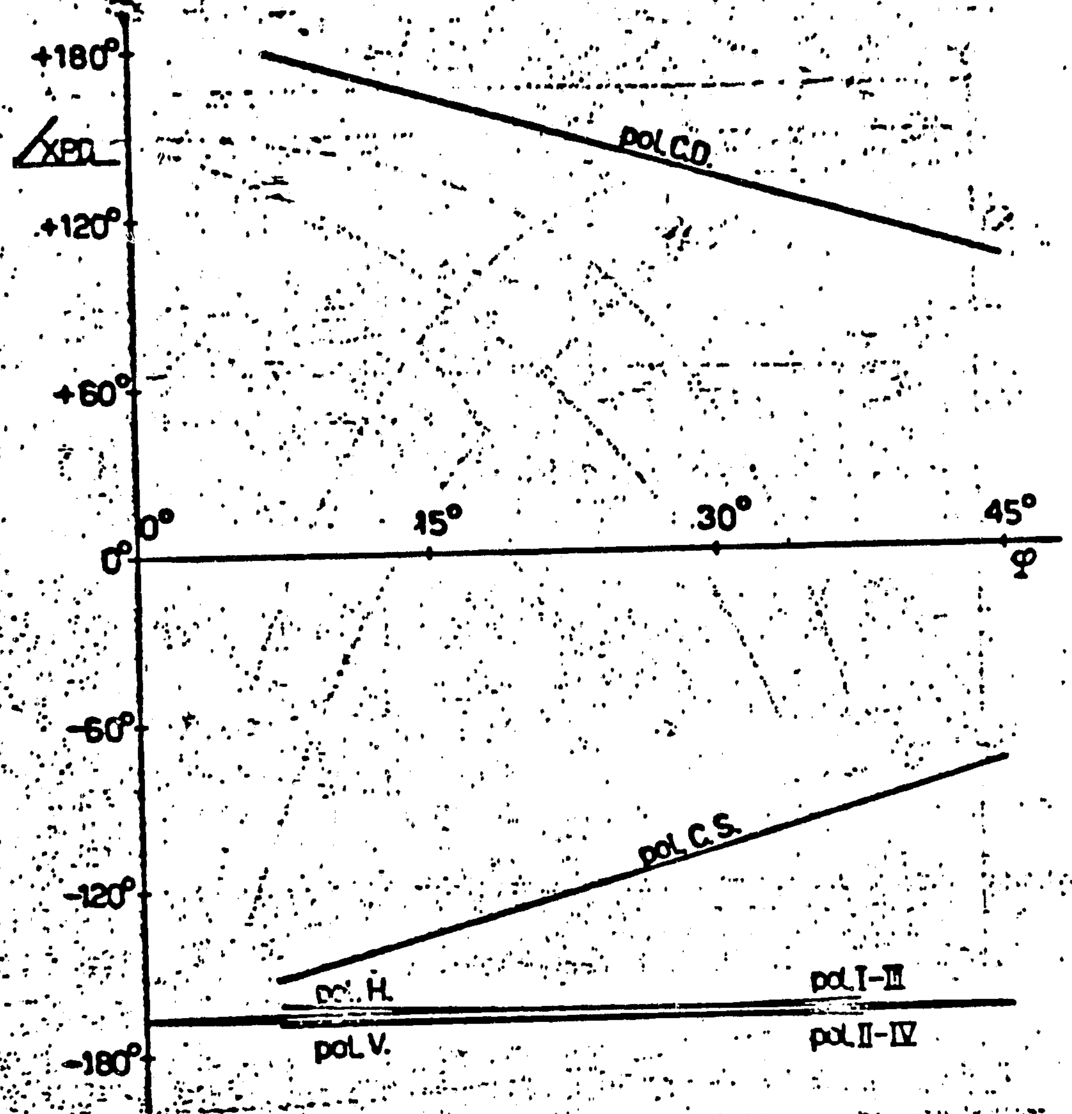
+180°
∠XPD
+120°
+60°
0°
0°
15°
30°
45°
φ
-60°
-120°
-180°
pol.C.D.
pol.C.S.
pol.H.
pol.V.
pol.I-III
pol.II-IV

FIG. 5